# Vibration analysis of a UAV multirotor frame

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## Abstract

Recent years have seen a huge increase in the development and use of small unmanned aircraft, otherwise known as drones or Unmanned Aerial Vehicle (UAV). A lot of published research work focusses on new applications, control optimization and flight range maximization. However, there is very little published work that deals with a thorough structural vibration analysis of a typical UAV chassis.

This paper discusses the experimental and numerical vibration analysis of a multirotor chassis. The paper provides an analysis of the main vibration sources affecting this UAV and an experimental modal analysis of the main structural components of the multirotor chassis. The resulting data is applied to a numerical modal analysis of the UAV chassis and allows, for instance, locating low-vibration regions where sensitive electronics should best be mounted.

## 1 Introduction

Recent years have seen a huge increase in the development and use of small Unmanned Aerial Vehicles (UAVs) for various applications such as photography, infrastructure inspection and agricultural applications [1]. Although the vehicles are primarily remotely controlled, vehicle stabilization and navigation is usually assisted by an onboard autopilot relying on miniature sensors such as accelerometers, gyroscopes, barometer, GPS and more.

Precise control of a UAV begins with accurately estimating its attitude and position [2]. This state estimation is primarily based on measurements of the autopilot’s miniature accelerometers and gyroscopes. Sensing even the smallest changes in attitude requires a stiff frame while keeping the vibration levels as low as possible to minimize signal noise and as a result minimize multirotor drift from its desired position. However, there is very little published work that performs a thorough structural vibration analysis of a typical UAV frame.

Helicopter type aircraft have higher vibration levels than fixed-wing aircraft due to their lift being generated by one or more high-speed rotors subject to unsteady aerodynamic effects. The most common helicopter type UAV is a multirotor which has three or more rotors to lift and control the platform [3] (Figure 1). Most multirotor platforms utilize fixed-pitch propellers that control the platform by changing their rotational velocities. The maximum number of propellers is unlimited. The main advantages of a multirotor compared to a conventional helicopter, with a main and tail rotor, are its inherent high agility, compactness and lack of swashplate resulting in increased reliability.

This paper is part of a research project in which an autonomous unmanned rotary UAV is designed, constructed and flight tested for inspecting fruit orchards and vineyards by flying autonomously in between the (narrow) tree rows in outdoor conditions such as wind and gusts [4]. The autonomous navigation requires combining collision avoidance in a confined area through GPS-trajectory tracking, sonars and forward camera corridor detection and shared control for a safety pilot. The forward camera corridor detection task performs real-time image processing to find the middle of the corridor in the image and estimate the UAV's drift with respect to this middle as standard GPS is not accurate enough and its signal could be distorted by the trees. Accurate state estimation is key to minimizing drift of the multirotor in the narrow corridors. A good combination of a stiff frame and low vibration levels is therefore essential and was the main motivation for the research presented here.

Figure 1: Hexacopter UAV frame (Quadframe)

This paper discusses the experimental and numerical vibration analysis of a multirotor frame, more specifically a six armed multirotor (hexacopter) made by Quadframe (Figure 1). The paper is structured as follows: Section two of this paper analyses the main vibration sources for a multirotor frame: the six electrically driven motors and corresponding propellers. Section three focusses on an experimental modal analysis of the main structural components of the hexacopter frame, including simplifications to the test structure, and hammer impact and shaker excitation methods used. Section four extensively deals with the numerical modal analysis of the hexacopter frame. Firstly, it outlines the finite element model setup, simplifications and assumptions that are made to make the model computational efficient and robust. Secondly, it extensively discusses the motor-propeller vibration excitation modelling and implementation in the model. Furthermore, it identifies the lowest vibration level locations on the frame where the sensitive electronics ideally should be mounted. The paper finalizes with some important conclusions on this research work and prospects to ongoing and future research activities in this area.

# 2 Motor-propeller induced vibrations

In the process of numerical modal analysis on the proposed multicopter frame, the accurate analysis of the main vibration sources is crucial. The outlined approach mainly consists of two phases: (i) experimental determination of the vibration sources and (ii) its implementation in the structural FE model.

## 2.1 Experimental determination

The first phase accurately quantifies the main sources that induce structural vibrations. The main vibration sources during normal operation of the multicopter are the different motor – propeller units. In order to perform an accurate FE vibration analysis, the vibrations induced by these virtually identical drive units are experimentally determined. Two similar test setups are considered for this, one for the measurement of axial oscillating forces and a second one to measure the radial vibration forces. Figure 2 illustrates the test setup in which two force transducers are mounted between the electric motor housing and the environment. Two transducers are considered in order to minimize the erroneous effect of the force cells also capturing bending moments instead of pure uniaxial forces.

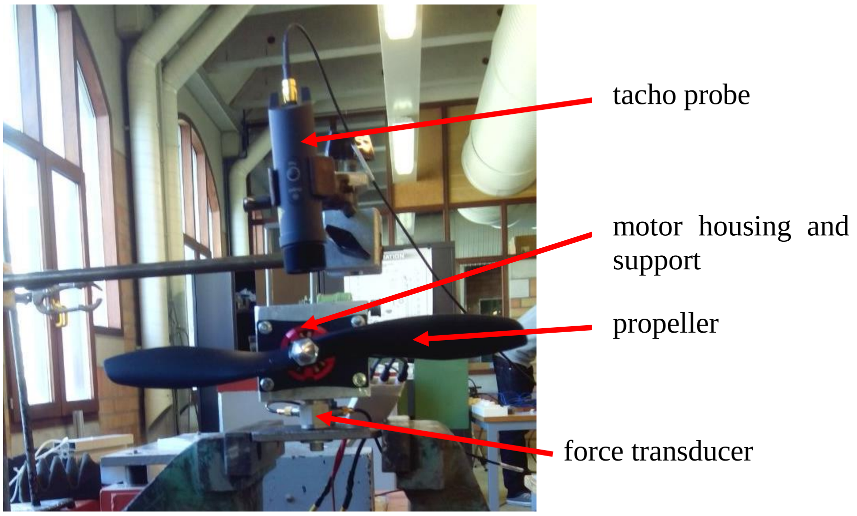



Figure 2: Experimental setup for radial vibration force measurements

Both the axial and radial vibrations are determined at different rotational speeds, ranging from 200 to 14500 rpm. Three cases are considered: motor without propeller, motor with wooden propeller and motor with plastic propeller. Figure 3 shows a typical recorded radial force signal for motor induced vibration in the case where no propeller is mounted.

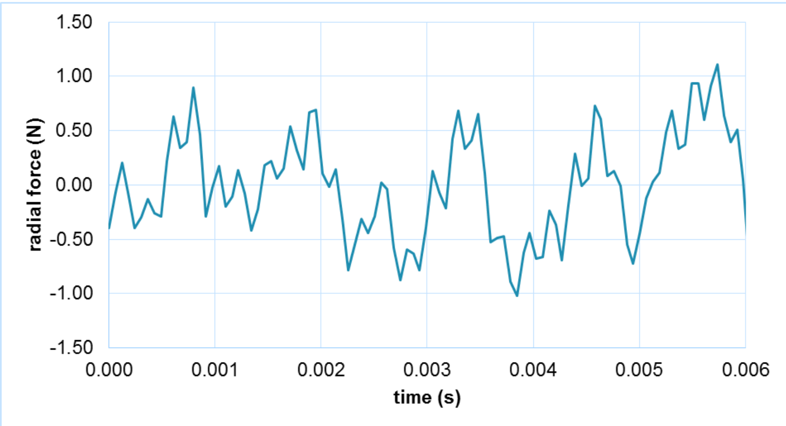



Figure 3: Experimentally determined dynamic radial force (motor with no propeller fitted)

The overall low recorded force levels in case no propeller is mounted, indicate that the latter is the main source for both axial and radial vibrations. Figure 4 shows the radial force spectrum in case a plastic 10” propeller is mounted. The rotation frequency during this test is 86 Hz, corresponding to 5160 rpm.

When a standard plastic propeller is installed, the registered radial vibration force amplitude ranges from 0.1 N at 500 rpm to 5.9 N at 4000 rpm (8” plastic propeller). The stated (nearly) quadratic relation between the force amplitude and rotation frequency clearly indicates propeller unbalance.

## 2.2 Implementation in the structural FE model

In a second phase, the experimentally determined axial and radial vibration patterns, discussed above, are processed so that they can be implemented in a structural numerical FE model. During normal usage of the considered hexacopter platform and dictated by flight conditions, the six nominally identical motor-propeller units act as different vibration sources because their rotation speed can be controlled individually. This causes the vibration force amplitudes to be different for each drive unit. Moreover, the phase difference between all units is random at any time. For reasons of computational efficiency the vibration force spectra, captured for each drive unit at different rotation speeds, are combined to single excitation force spectra for both axial and radial cases. This is done in a bandwidth of 600 Hz. The spectrum in figure 5 shows the obtained axial force excitation that is used for the structural FE vibration analysis.

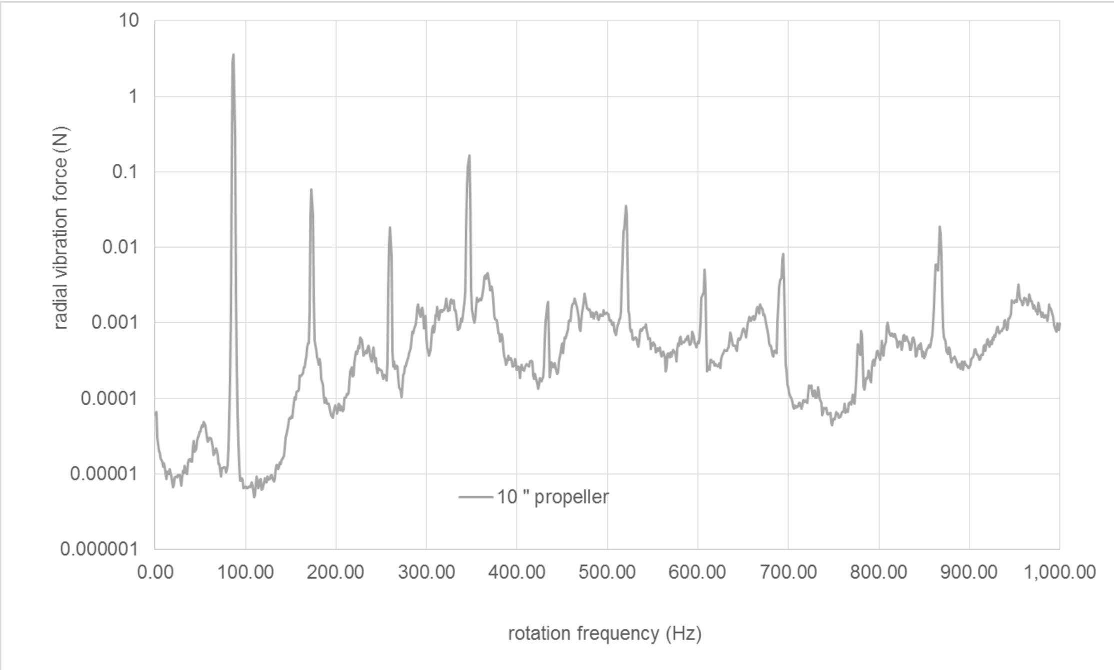



Figure 4: Spectrum of experimentally determined dynamic radial force (10” plastic propeller fitted)

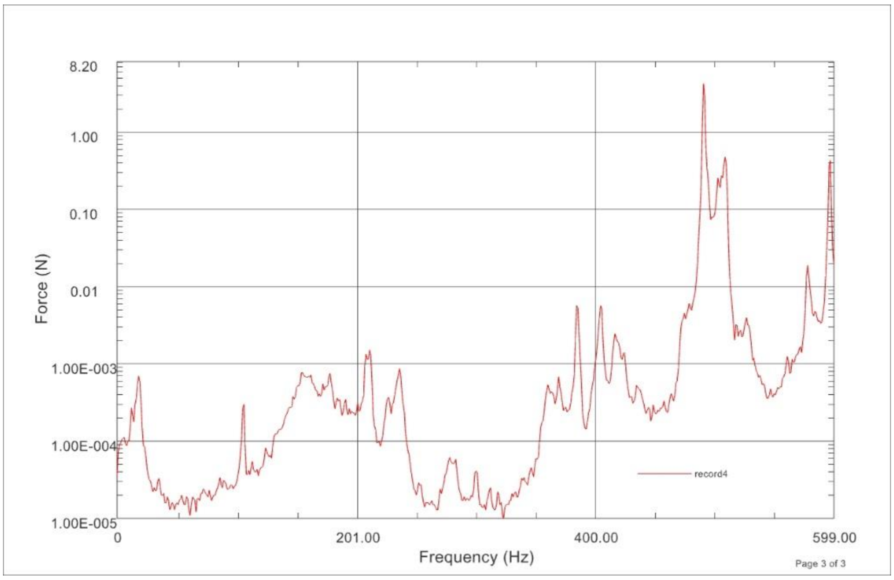



Figure 5: Axial force spectrum, applied in FE structural model

This approach enables to provide a structural FE model of the hexacopter chassis with radial and axial excitation force spectra. These force spectra are applied at the motor fixation points, as indicated by figure 6. The mass of each drive unit is added to the model as a discrete mass, located at the centring collar.

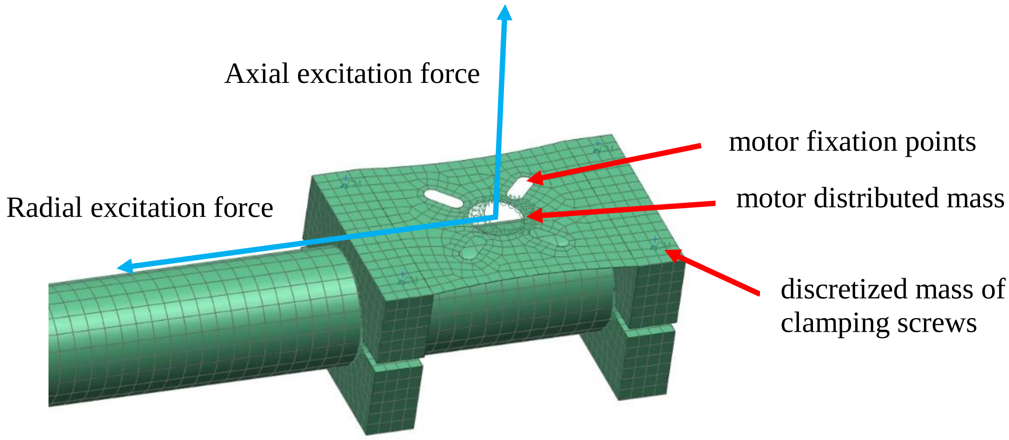



Figure 6: Indication of drive unit mass and force excitations in FE model

For each of the six drive units, the vibration force excitation spectrum is applied in a similar way. The phase shift between the different radial force spectra is considered to be random, which corresponds to the real application conditions.

# 3 Experimental modal analysis on the multicopter frame

This section describes the process of the experimental vibration analysis of the hexacopter frame and its individual components. Specific attention is given to the estimation of relevant elastic material properties by means of reverse engineering [5].

## 3.1 Estimation of important elastic material properties

The performance of any structural FE model strongly depends on the accuracy of the relevant material properties. For the type of analysis discussed here, stiffness and mass properties are important. This study applies a mixed experimental-numerical approach to estimate these characteristics for the materials of the main structural components of the hexacopter frame which are the six tubular arms (1), the centre plates (2) and the clamping blocks (3), as illustrated by figure 7.

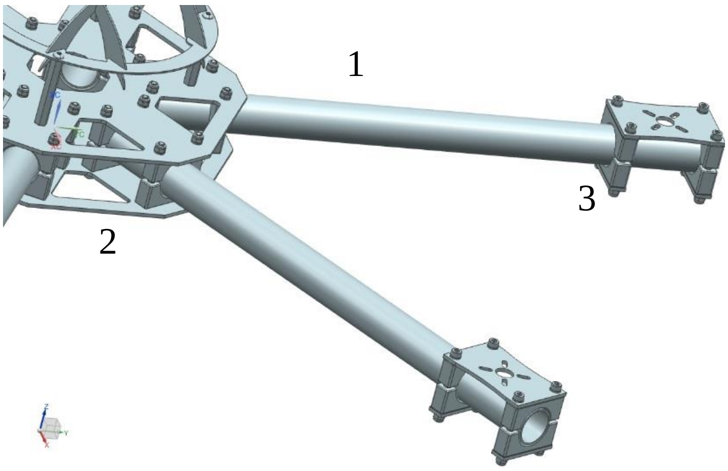



Figure 7: Main structural parts in the hexacopter frame

For each of the components mentioned above the geometry and mass are measured accurately. To estimate the stiffness characteristics of the tubes, for instance, one of these is rigidly clamped using the corresponding blocks (nr. 3 in figure 7) and subjected to hammer excitation tests. The frequency response function in figure 8 clearly shows two resonance frequencies in the frequency range considered. The bending mode occurs at 130 Hz while the second one has a frequency of 984 Hz.

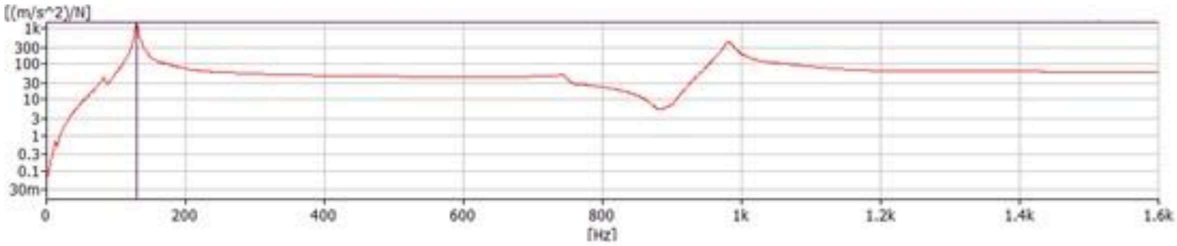



Figure 8: Registered frequency response function for arm assembly

Modelling this experiment by providing the same boundary conditions to the clamping blocks and applying a FE model updating [6] routine yields a modulus of elasticity of 28.5 GPa and a mass density of 1647 kg/m³ for the tube material. The same reverse engineering yields the stiffness of the centre plates. Standard bolts joints (Metric thread M4) are used to join the clamping blocks to the tubular arms on the side of the centre plate and to fix the drive units to the arms on the other side. In the FE model they are considered as cylindrical steel rods, with their correct mass incorporated in the model.

## 3.2 Hammer excitation tests on complete frame

The complete hexacopter frame is assembled and subjected to vibration tests. In order to eliminate boundary effects, the frame is elastically suspended, as shown by figure 9.

Figure 9: Elastic suspension of hexacopter frame

The impulse hammer excitation method is used for the experimental modal analysis. Three lightweight accelerometers of 0.5 grams each capture the dynamic response of the structure. A set of 75 excitation points is considered along the complete structure. In a frequency range of 800 Hz, 7 resonance mode shapes can clearly be defined. Table 1 gives an overview.

The next section describes how these experimental results are implemented to validate the FE dynamic model of the structure.

| mode | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| **Frequency (Hz)** | 86 | 93 | 106 | 120 | 312 | 339 | 672 |
| **Damping ratio (%)** | 1.58 | 1.38 | 1.41 | 1.22 | 0.85 | 0.76 | 0.72 |

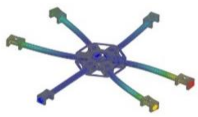
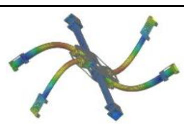
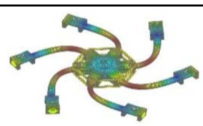
Table 1: Experimentally determined resonance frequencies and damping ratios of complete hexacopter frame

# 4 Numerical modal analysis

This section outlines the approach that is used to analyse the hexacopter's frame dynamics by means of structural FE modelling. The applied approach is twofold. Firstly, the resonance behaviour of the frame is calculated under free boundary conditions. Secondly, vibration levels at the centre plate are determined. This is relevant because all electronic devices (control, applications) are mounted on this plate.

## 4.1 Structural resonances

A FE model of the whole hexacopter frame is constructed. For this purpose, the centre plates and the tubular arms are meshed using shell elements while the clamping blocks are meshed using volume elements. All bolt connections are modelled as rod elements to include their stiffness in the model. The additional masses of the bold heads, nuts and washers are added to the model as discrete masses. For each of the six drive units (motor and propeller), only the total mass is discretized at the four fixation slots and the circular collar. Table 2 visualizes a set of seven obtained resonances (frequencies and mode shapes) and compares the simulation with the experiments from section 3. Mode shapes are compared using the MAC [7].

| mode | Resonance frequency numerical (Hz) | Resonance frequency experimental (Hz) | Relative difference (%) | Mode shape | MAC (%) |
|---|---|---|---|---|---|
| **1** | 86 | 86 | 0,047 |  | 0.91 |
| **2** | 92,8 | 93 | 0,205 |  | 0.9 |
| **3** | 104,2 | 106 | 1,727 |  | 0.92 |
| **4** | 121,3 | 120 | 1,072 |  | 0.95 |
| **5** | 303,8 | 312 | 2,699 |  | 0.94 |
| **6** | 329,6 | 339 | 2,852 |  | 0.88 |

| | | | | | |
|---|---|---|---|---|---|
| **7** | 673,6 | 672 | 0,238 |  | 0.79 |

Table 2: Comparison between numerical and experimental resonance behaviour of the complete frame

Table 2 clearly indicates a good match between the experimental and numerical results. The following paragraph incorporates the vibration excitations of the six drive units into the FE model and uses the model to calculate the vibration levels at different locations on the centre plate.

## 4.2 Dynamic response at critical locations

Once the resonance behaviour of the hexacopter structure is determined and a good FE model is established, this can be used to perform an application related vibration analysis. In this case, the model is used to calculate vibration levels of the centre plate, more specific at the locations which are used to mount electronic devices and circuit boards. On the one hand, this analysis is necessary for durability estimation of electronic components used. On the other hand, it is relevant to estimate the stability of on-board optical sensors and cameras.

The radial and axial drive unit vibrations, characterized in section 2, are incorporated into the structural FE model. As mentioned in section 2 the six drive units act independently from each other to some extent. In the application context this is necessary for reasons of controllability of the aircraft. Therefore the corresponding six radial excitation force spectra are applied with a random mutual phase angle shift. At this stage of the research, the six axial excitation force spectra are modelled identically. This relates to the application situation where all drive units rotate with the same speed. Figure 10 shows a calculated FRF that illustrates the vibration deformation at one of the fixation points at the upper centre plate.

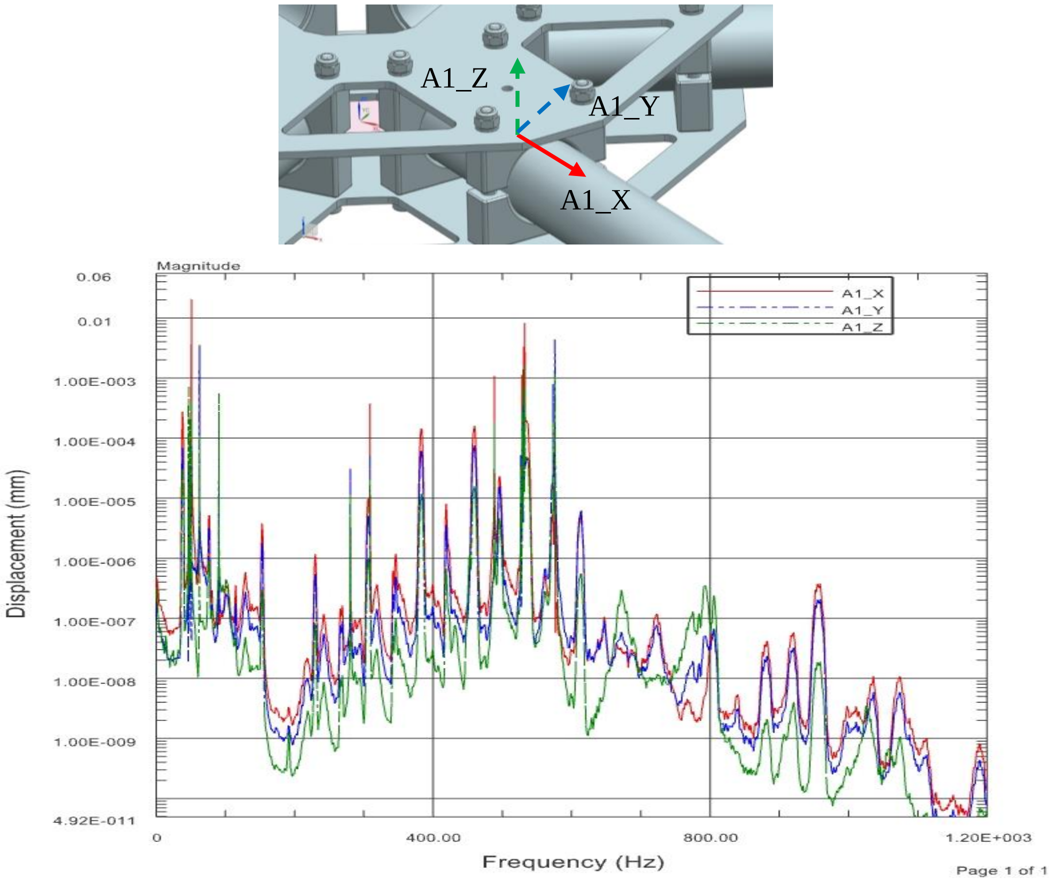



Figure 10: Upper: indication of A1 location on centre plate; Lower: example of calculated FRF's at different directions X, Y and Z at location A1

The calculated vibration levels, in figure 10 for example, give a clear indication of the expected operational vibrations that occur during normal usage of the device. This should be taken into account when selecting and mounting electronic components on the frame.

# 5 Conclusions and research prospects

This article discusses the application of the modal analysis technique on a multicopter chassis. In the context of RPAS, a thorough dynamic structural analysis is novel up till now. However, it is most relevant and crucial to uptake this type of analysis in any new RPAS design.

This paper discussed the applied methods in general. It shows that a sound balance between experimental and numerical work yields very accurate and reliable results.

Current research efforts focus on accurate real-time in-flight vibration measurements on the one hand, and more elaborate FE models that include all relevant (also non-structural) components on the other hand.

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